

COHERENT SCALAR FIELD OSCILLATIONS AND THE EPOCH OF DECELERATION

by

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ABSTRACT

The discovery of supernova SN 1997ff at $z \sim 1.7$ has confirmed the expected switch from cosmological acceleration to deceleration, as predicted by the concordance Λ /CDM model. However its position in the SN Ia Hubble diagram suggests that the switch is too pronounced, which here is taken to mean that a cosmological constant is not an adequate description of the state of the vacuum. An ‘oscillessence’ model is invoked, with a scalar field ϕ governed by a simple quadratic potential, which gives a better fit to the new data point. The field is undergoing coherent oscillations, and a key feature of the proposal is that we are towards the end of the second period of acceleration; a Λ/ϕ mix replaces Λ /CDM, with $\Omega_\Lambda \sim 0.4$ and $\Omega_\phi \sim 0.6$.

Key words: cosmology – observations – theory – dark matter.

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1 INTRODUCTION

There is now a strong consensus that the basic cosmological parameters are known, and that we are living in a spatially flat accelerating Universe, with $\Omega_{\text{CM}} \sim 0.3$ and $\Omega_{\Lambda} \sim 1 - \Omega_{\text{CM}} \sim 0.7$ (CM \equiv Cold Matter, that is Cold Dark Matter plus the baryonic component). This consensus is based primarily upon observations of Type Ia supernovae (SNe Ia) (Schmidt et al. 1998; Riess et al. 1998; Perlmutter et al. 1999), coupled with observations of Cosmic Microwave Background (CMB) anisotropies (Efstathiou et al. 1999) and Large Scale Structure (LSS) information (Bridle et al. 1999; Lasenby, Bridle & Hobson 2000; Efstathiou et al. 2001). Separately these observations place different constraints on the parameter values, but in combination degeneracies are removed. However, the CMB measurements have been refined through a number of ground-based and balloon-borne experiments (Halverson et al. 2001; Lee et al. 2001; Netterfield et al. 2001), particularly significant being the detection of multiple peaks in the CMB angular power spectrum, and the data sets are now beginning to tell the same story when considered separately (Balbi et al. 2000; de Bernardis et al. 2001; Jaffe et al. 2001; Pryke et al. 2001; Stompor et al. 2001). Support for flatness comes from measures of the angular size of the acoustic horizon at decoupling, via detection of the first Doppler peak in the CMB angular spectrum (de Bernardis et al. 2000; Hanany et al. 2000); for this reason I shall restrict my attention to spatially flat models.

This impressive convergence of independent measures of the various cosmological parameters is coming to be known as ‘concordance’, and the corresponding cosmological model as the concordance model. The concordance model predicts a transition from acceleration to deceleration at a redshift $z = (2\Omega_{\Lambda}/\Omega_{\text{CM}})^{1/3} - 1 \sim 0.67$, beyond which the matter density is dominant; the discovery of SN 1997ff (Gilliand & Phillips 1998), together with fortuitous retrospective multicolour photometric observations which have established its type, a redshift $z \sim 1.7$ and a distance modulus, provide strong evidence that the epoch of deceleration has been observed (Riess et al. 2001). I shall address here what appears to be a discordant note arising from these observations, which is a strong suggestion that the switch to deceleration is too violent. Figure 1 is a Hubble diagram for SNe Ia, reproducing the results presented in Figure 11 of Riess et al. (2001), in which the points with error bars are redshift-binned data from Riess et al. (1998) and Perlmutter et al. (1999); here the magnitude Δm is relative to an empty non-accelerating universe. The cross shows SN 1997ff at $z = 1.7$, $\Delta m = -0.5$, and the corresponding 68% and 95% confidence regions are indicated. The continuous curve is an unweighted least-squares fit to the $z < 1$ points, ($\Omega_{\text{CM}} = 0.28$, $\Omega_{\Lambda} = 0.72$), which clearly illustrates the point I am making here. The dashed curve shows an unweighted least-squares fit to all the points ($\Omega_{\text{CM}} = 0.44$, $\Omega_{\Lambda} = 0.56$); the extra matter produces more deceleration, but destroys the good fit to the $z < 1$ points. The possibility discussed here is that this behaviour is evidence that a simple cosmological constant is not an adequate description of the present state of the vacuum, and the purpose of this letter is to present a simple alternative which is compatible with the SN Ia Hubble data, and might at the same time do least damage to the concordance picture.

2 Λ/ϕ MODELS

Some time ago (before the case for acceleration was as strong as it now appears to be) (Jackson 1998a,b; Jackson & Dodgson 1998; see also Frieman et al. 1995) I considered models dominated by a homogeneous dynamical scalar field ϕ governed by an inflationary potential corresponding to an ultra-light inflaton:

$$V(\phi) = \frac{\Lambda}{8\pi G} + \frac{1}{2}\omega_c^2\phi^2 \quad (1)$$

where ω_c is the associated Compton frequency, here taken to be somewhat larger than the inverse of the present Hubble time. The scalar field has effective density $\rho_\phi = (\dot{\phi}^2 + \omega_c^2 \phi^2)/2$ and pressure $p_\phi = (\dot{\phi}^2 - \omega_c^2 \phi^2)/2$. The most convenient formulation of the Friedmann equations governing the scale factor $R(t)$ is in terms of the instantaneous values of the deceleration parameter $q(t)$, and the various density parameters $\Omega = 8\pi G\rho/3H^2$; in the spatially flat case these are

$$q = \Omega_{\text{CM}}/2 + (1 + 3w)\Omega_\phi/2 - \Omega_\Lambda \quad (2)$$

and

$$\Omega_{\text{CM}} + \Omega_\Lambda + \Omega_\phi = 1 \quad (3)$$

where w is the ratio p_ϕ/ρ_ϕ .

The scalar field is governed by the equation

$$\ddot{\phi} + 3H\dot{\phi} + \omega_c^2 \phi = 0, \quad (4)$$

where $H = \dot{R}/R$ is Hubble's 'constant'. Initially (when $H \gg \omega_c^{-1}$) the field ϕ undergoes a slow roll towards the minimum in $V(\phi)$ at $\phi = 0$, during which phase the effective cosmological constant is $\Lambda + 4\pi G\omega_c^2 \phi^2$. This is the standard inflationary picture, but in this context the pressure-free matter is assumed to be dynamically dominant during the slow-roll phase. Thereafter, when $H < \omega_c^{-1}$, ϕ undergoes coherent oscillations, and the speculation here (and in Jackson 1998a,b; Jackson & Dogson 1998) is that the Universe has entered a phase in which the scalar field is dynamically dominant and is executing such oscillations. During this phase periods of violent deceleration (when $\rho_\phi + 3p_\phi > 0$) alternate with periods of not-so-violent acceleration (when $\rho_\phi + 3p_\phi < 0$), which behaviour can account for the SN 1997ff observations. Figure 2 is a typical example, showing the evolution of the deceleration parameter $q(t)$ and the age/Hubble time ratio t/t_H . In what follows I shall assume generically that we are currently at point P, at the end of the second period of acceleration, to maximise the effect of the latter. In the example shown the parameter values at P are $\Omega_{\text{CM}} = 0.012$, $\Omega_\Lambda = 0.433$, $\Omega_\phi = 0.555$; their sum is 1 as dictated by equation (3), and $q = 0$ at P fixes w (or equivalently ϕ and $\dot{\phi}$) and hence the model according to equation (2). Locally these values give the best fit to the SN Ia data, including SN 1997ff; the corresponding curve is shown in Figure 3. Observation points located during the first period of acceleration do no better in this respect than straightforward Λ/CM models, as in Figure 1. Even later periods of acceleration might be considered, but the corresponding Hubble curves generally have features for which there is no evidence.

An interesting possibility is that just the quadratic term in the potential (1) might suffice, with no true cosmological constant, but this is discounted by the dashed curve in Figure 3, with $\Omega_{\text{CM}} = 0$, $\Omega_\Lambda = 0$, $\Omega_\phi = 1$; deceleration sets in too soon in this case, and addition of some Cold Matter would clearly make the situation worse. The picture which emerges here is that of a mixed Λ/ϕ model, with a low Cold Matter content, of the order of the baryon content of the Universe (see Coc et al. (2001) for a recent review). If SN Ia data were the only consideration then this model would be perfectly viable, but almost certainly not compatible with CMB and LSS. However, there are acceptable models (i.e. when SN 1977ff is included) with more Cold Matter (but not more than $\Omega_{\text{CM}} \sim 0.1$), which nevertheless probably are compatible. This universe is heading for heat death, with a final oscillatory flourish before oblivion; this is illustrated in Figure 4.

I have allowed blatant fine-tuning here, with no attempt to account for the balance between the two components of dark energy. Following the seminal work of Ratra & Peebles (1988) and Wetterich (1988), who considered decaying potentials of the form $V(\phi) \propto \phi^{-\alpha}$ and $V(\phi) \propto \exp(-\alpha\phi)$, the manufacture of scalar-field models has evolved into a large industrial concern, particularly post 1998 and particularly with view to accounting for the balance between dark energy and dark matter in a natural way (see Bean and Melchiorri (2001) for a recent review). Some of the corresponding potentials also engender oscillatory behaviour (for example Frieman et al. 1995; Skordis & Albrecht 2000), and might serve as alternatives to equation (1) in the present context. Alternatively, if the simplicity of potential (1) is to be preferred, then an anthropic argument might be found to account for the putative balance. The generic term ‘oscillessence’ might be reserved for dark energy which allows multiple periods of acceleration/deceleration (cf. Caldwell, Dave & Steinhardt 1998).

FIGURE CAPTIONS

Figure 1. Type 1a supernovae and Λ /CM models. Hubble diagram relative to to an empty non-accelerating universe. The cross indicates SN 1997ff, with 68% and 95% confidence regions. The continuous curve shows a concordance model ($\Omega_{\text{CM}} = 0.28$, $\Omega_{\Lambda} = 0.72$); the dashed curve is the best fit to all the data points ($\Omega_{\text{CM}} = 0.44$, $\Omega_{\Lambda} = 0.56$).

Figure 2. An oscillating model, showing the evolution of the deceleration parameter $q(t)$ (continuous) and the ratio t/t_H (dashed). The current observation point is located at P, where $\Omega_{\text{CM}} = 0.012$, $\Omega_{\Lambda} = 0.433$, $\Omega_{\phi} = 0.555$.

Figure 3. Type 1a supernovae and Λ/ϕ models. Hubble diagram relative to to an empty non-accelerating universe. The cross indicates SN 1997ff, with 68% and 95% confidence regions. The continuous curve shows the best fitting Λ/ϕ model, with parameters as in Figure 2. The dashed curve has parameters $\Omega_{\text{CM}} = 0$, $\Omega_{\Lambda} = 0$, $\Omega_{\phi} = 1$. The dash-dot curve is the concordance model as in Figure 1.

Figure 4. Oscillating model showing the evolution of various density parameters $\Omega = 8\pi G\rho/3H^2$; Ω_{CM} (dotted), Ω_{Λ} (dashed), Ω_{ϕ} (continuous). The dash-dot curve is a composite parameter based upon the active gravitational density $\rho_{\phi} + 3p_{\phi}$.

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